

**REVIEW OF
1963-1966 SACK RESEARCH PROGRAM**

Project 2033
Report Thirty-nine
A Progress Report
to
MULTIWALL SHIPPING SACK PAPER
MANUFACTURERS RESEARCH GROUP

June 21, 1966

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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REVIEW OF 1963-1966 SACK RESEARCH PROGRAM

SUMMARY

During the contractual period the research program was divided into two main phases. The first phase was devoted to a comprehensive analysis of the relationships between face and butt drop performance and the conventional sack paper properties. It was believed that the results of the analysis might be utilized in practical applications directed toward improvements in sack paper manufacture and performance. The second phase was concerned with the analysis of the mechanics of sack impact and related topics. A better understanding of the phenomena occurring during sack impact should help define those properties of sack paper which are important to sack performance and, in turn, stimulate research directed toward improvements in sack paper. The following briefly summarizes the results obtained:

1. Based on the statistical results and other factors (calibration, test time, etc.) it appears that combined T.E.A. is the best conventional sack paper property for predicting face drop performance. No combinations of sack paper properties were found which marked by improved face drop predictions as compared to combined T.E.A.

2. Butt drop appears to be primarily related to C.D. T.E.A. However, some improvement in prediction accuracy can be achieved by using (1) M.D. and C.D. T.E.A., or (2) C.D. T.E.A., C.D. tensile and C.D. tear. Using M.D. and C.D. T.E.A. about 80% of the predictions were within $\pm 20\%$ of the observed butt drop value.

3. These results indicate that the tensile energy absorption characteristics of sack paper are vital to drop test performance. Further work in the pulping and papermaking operations should be directed toward the goal of further commercially improving T.E.A.

4. To investigate sack impact behavior it was necessary to develop a means for measuring the strains in the sack walls that would not suffer from the reinforcement problems encountered with conventional wire grid strain gages. Considerable time was required to develop a conductive coating suitable for strain measurement. The conductive coating gage has many advantages for studying sack impact behavior and should be valuable for future work.

5. Studies of sack impact strains to date appear to indicate the following:

- a. Strain wave propagation may be an important consideration in sack impact. As one consequence, certain locations in the sack walls may suffer rapid increases in strain due to wave reinforcement. Higher local strains in the center of the sack face may be explained on this basis.
- b. The nonrecoverable strain in the sack paper increases with each succeeding drop. Thus, the fatigue performance of sack paper is of importance.

6. A limited study of local tension strains in sack paper revealed considerable differences in strain response. Failure usually occurs in the regions of greatest strain. Thus, two papers with the same average strain might have quite different local strain distributions with a consequent effect on their performance.

7. High-speed tension and sonic modulus methods of evaluating sack paper have been studied because of the rapid strain occurring during sack impact.

Further studies in this area are needed to clarify the problems encountered and to better define their significance to sack performance.

8. Because in face drop at least, the sack walls are strained in both directions, a study is underway to evaluate sack paper behavior in biaxial tension. This approach should help clarify the dependence of biaxial tension behavior on the M.D. and C.D. properties of the paper web and assist in stimulating efforts to improve sack paper performance.

INTRODUCTION - REVIEW OF RESEARCH

During the present contractual period the research program has been divided into two main phases. The first phase is devoted to a comprehensive analysis of the relationships between (a) face drop and (b) butt drop and the conventional sack paper properties. The second phase is concerned with the analysis of the mechanics of sack impact and related topics.

The following is a resumé of the results obtained on the studies which have been pursued since the last meeting of the Technical Committee of the Multi-wall Shipping Sack Paper Manufacturers. The results will be reviewed in greater detail at the forthcoming meeting scheduled for July 12, 1966. It is hoped that the present resumé will serve as a premeeting briefing.

REVIEW OF RELATIONSHIPS BETWEEN SACK PAPER PROPERTIES
AND DROP TEST PERFORMANCE

GENERAL

During the contractual period, the policy committee requested that the available data from past work be reanalyzed so that the information might be utilized in practical applications directed toward improvements in sack paper manufacture and performance. For this reason a series of reports have been prepared which discuss in detail the relationships between face and butt drop performance and the conventional sack paper properties. The reports are listed below:

1. Report Twenty-Nine. Relationship between sack drop and sack paper properties. Part I. Face drop performance. Feb. 7, 1964.
2. Report Thirty-One. Relationship between sack drop and sack paper properties. Part II. Butt drop performance. Oct. 21, 1964.
3. Report Thirty-Four. Relationship between sack drop and sack paper properties. Part III. Multiple linear correlations between face drop performance and combinations of sack paper properties. Jan. 17, 1966.
4. Report Thirty-Seven. Relationship between sack drop and sack paper properties. Part IV. Multiple linear correlations between butt drop performance and combinations of sack paper properties. To be issued.

Unfortunately, a theoretical model of sack impact has not been available to aid the above studies. Because of the complexities associated with the energy interchange between sack paper and contents during impact, it has not been possible to carry out a mathematical analyses. Other phases of the research program have been directed toward developing an understanding of sack impact behavior through

measurements of the impact strains. These studies, however, had not progressed sufficiently to be of material assistance in studying the relationships between sack performance and paper properties.

For these reasons a statistical approach was employed. While a necessity in this case, the statistical approach cannot take the place of a thorough understanding of sack impact behavior.

The following summarizes the main conclusions reached in each report.

FACE DROP - SINGLE FACTOR RELATIONSHIPS

The properties giving the best and poorest predictions of face drop performance are illustrated in Fig. 1 and 2, respectively.

Flat Kraft Sack Papers

Averaging the flat kraft results for Studies 1 and 2, the five best sack paper tests for predicting sack performance were as follows:

- a. T.E.A. (tensile energy absorption), combined
- b. Stretch, combined
- c. Impulse, combined
- d. Frag, combined
- e. T.A. impact fatigue

Based on testing ease, calibration considerations and theoretical concepts, combined T.E.A. is preferred for specification or control of flat kraft multiwall sack paper.

Combined stretch, by itself, appears to offer almost as good predictive ability as T.E.A., which is a function of both tensile and stretch. However, this relation may hold only for papers of a given grade weight. It is well known that

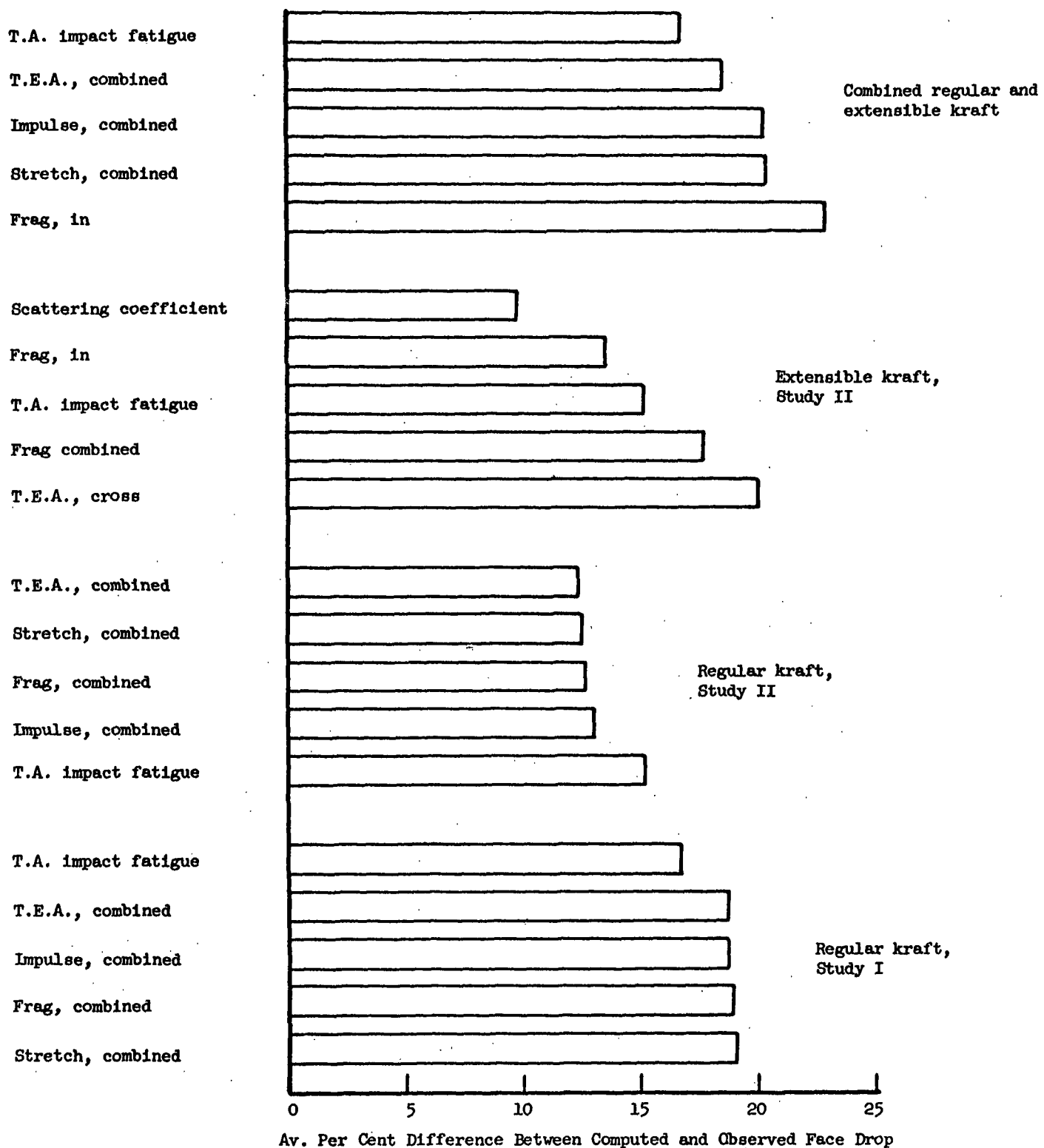


Figure 1. Comparison of Properties Giving the Best Predictions of Face Drop Performance

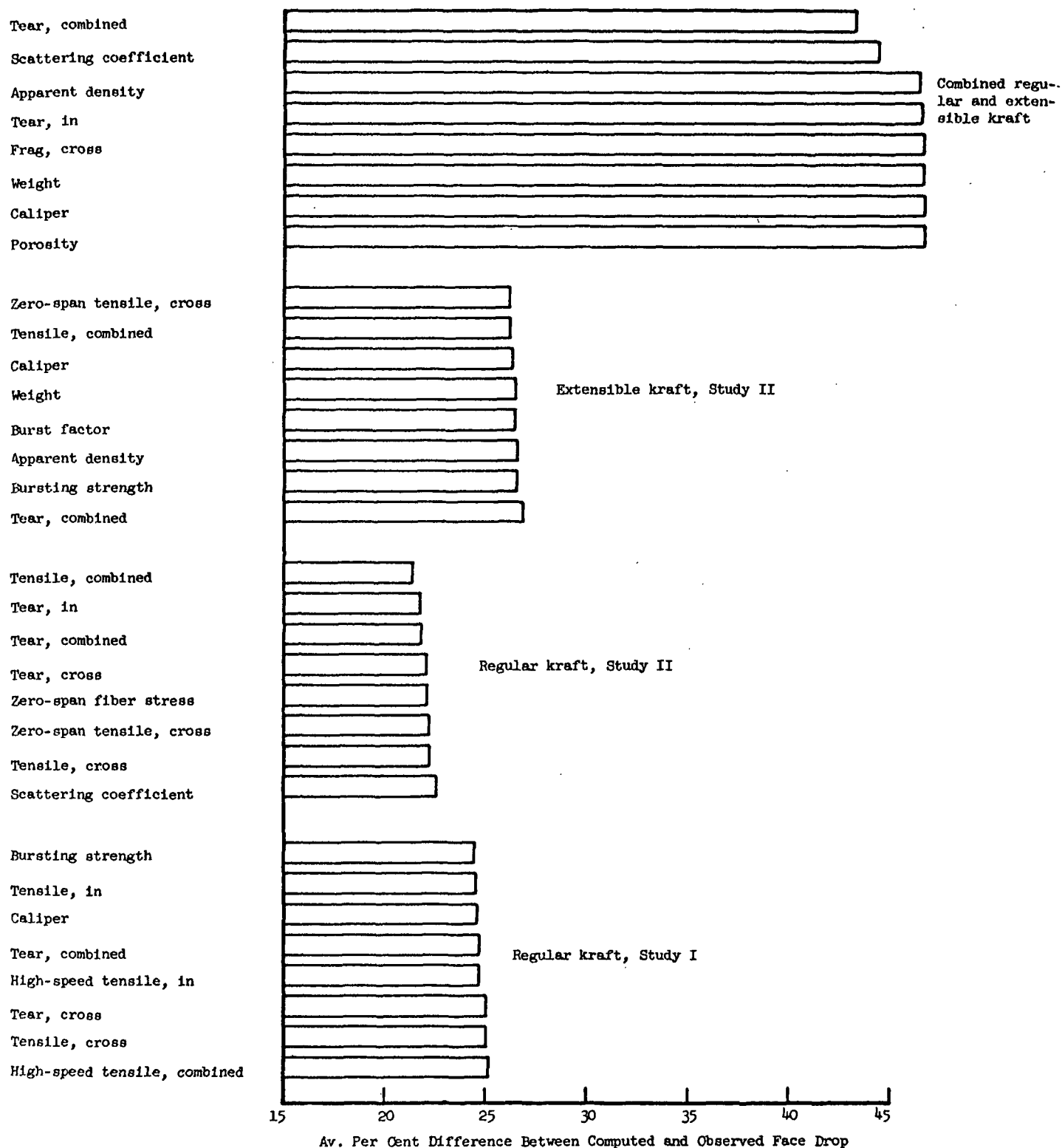


Figure 2. Comparison of Properties Giving the Poorest Predictions of Sack Performance

stretch is independent of weight. Therefore, if the relationship were applied to various grade weights, it would not be expected to hold. For example, a sack made with four plies of 60-lb. sack kraft would be expected to outperform a sack made with four plies of 40-lb. paper though each would have about the same combined stretch.

In contrast to stretch, tensile strength is strongly dependent on basis weight and, consequently, the tensile strength will increase as the weight increases. As a result T.E.A. which is a function of both tensile and stretch is expected to have more general application than either tensile or stretch alone.

Among the paper tests which were found to be less well related to face drop performance were bursting strength, tensile, and tearing strength.

Extensible Flat Sack Papers

The five best tests for predicting face drop performance of extensible paper sacks arranged in order of decreasing predictability are:

- a. Scattering coefficient
- b. Frag, in
- c. T.A. impact fatigue
- d. Frag, combined
- e. T.E.A., cross

Although scattering coefficient, Frag and T.A. impact fatigue are better related to face drop performance than T.E.A., cross, it is believed the latter is more amenable for use in specification, control, etc. The two impact fatigue tests are characterized by high variability and long testing time. Although scattering coefficient correlates the best for these 50-lb. extensible papers, its poor showing on flat kraft, lack of dependency on such things as fiber length, anisotropy of

the sheet, and relative humidity, raises doubts as to its usefulness as a criterion of quality by itself.

Among the sack paper tests found to be poorly related to face drop performance (see Fig. 2) were tearing strength, bursting strength, and M.D. tensile.

Extensible and Flat Kraft Sack Papers

The five best tests (see Fig. 1) arranged in order of decreasing predictive ability were:

- a. T.A. impact fatigue
- b. T.E.A., combined
- c. Impulse, combined
- d. Stretch, combined
- e. Frag, in

Taking test cost, calibration, etc., into account, combined T.E.A. seems to be the best single property for evaluating paper in terms of face drop performance for flat and extensible papers. Neither T.E.A. nor any of the test properties mentioned will accurately predict the relative performance of all papers. The use of these tests should, therefore, be tempered by judgment and experience.

The use of combined T.E.A. implies that in and cross-machine T.E.A. are equally important to face drop. This is probably an approximation and changes in combined T.E.A. accompanied by large changes in the directional ratio may have unpredictable effects on face drop.

The relationship developed from the data for 3-ply cement size sacks made from flat and extensible kraft papers is given by Equation (1).

$$F = -45.6 + 495.3 (W_x + W_y) \quad (1)$$

where F = face drop performance at 50% R.H., safe inches

W_x, W_y = T.E.A., M.D., and C.D., respectively, in lb./in.².

The above equation is an empirical relationship found for 3-ply cement sacks tested at 50% R.H. using 94 lb. of cement as the commodity. In addition to paper quality, sack performance is known to vary with type and amount of commodity, dimensions, style, and environmental conditions. Consequently, Equation (1) should not be used for general predictions of face drop performance. However, it can be used to predict the effect of changes in T.E.A. on face drop for the conditions employed, and it may be anticipated that such predictions will hold on a relative basis under many conditions.

FACE DROP - MULTIPLE FACTOR RELATIONSHIPS

An extensive analysis of past data was carried out to determine if predictions of face drop could be materially improved using various combinations of conventional sack paper properties. The results obtained for a small number of the more promising relationships studied are shown in Fig. 3. Relationships involving scattering coefficient or fatigue properties are excluded from this summary in view of their disadvantages for specification or mill control. For comparison, the results obtained with combined T.E.A. alone are also shown in the figure.

Flat Kraft Sack Papers

For these 50-lb. flat kraft papers, using combined T.E.A. with either combined tear or combined tensile in two-factor equations gave only small improvements in correlation relative to combined T.E.A. alone. The three-factor relationship employing combined T.E.A., tear, and tensile also failed to show much improvement over combined T.E.A. alone.

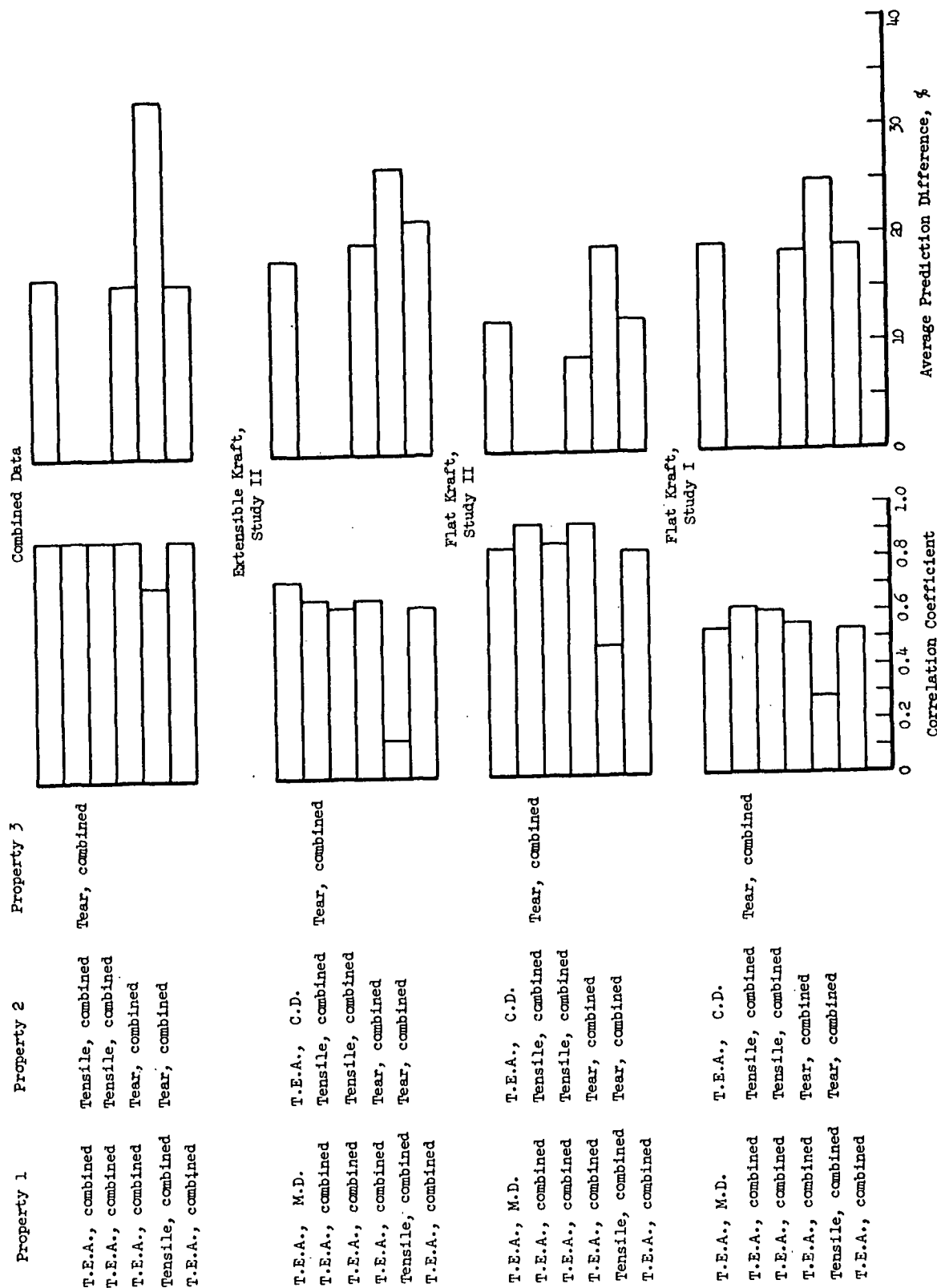


Figure 3. Comparison of Various Multiple Factor Relationships for Predicting Face Drop

For the 50-lb. flat kraft sack papers, T.E.A. appears to be the more important sack paper property in so far as face drop performance is concerned. On the basis of these data, tensile and tearing strength do not appear to be of major importance to face drop performance of flat kraft. However, they may be of importance in other aspects of sack performance - e.g., snagging, nail tears, etc.

The above is also shown by the fact that the two-factor relationship using combined tensile and combined tear gave poorer results than combined T.E.A. alone. It was also shown in Report Thirty-Four that the same conclusion was obtained using either the M.D. or C.D. orientations. It is concluded, therefore, that tensile and tear taken separately or together are not well related to the face drop performance of pasted sacks made from 50-lb. flat kraft.

Treating machine and cross-machine T.E.A. as separate factors in a two-factor relationship gave no marked advantage over combined T.E.A. - in which the two directions are given equal weight.

Extensible Kraft Sack Papers

As in the case of the flat kraft results the two or three-factor relationships involving combined T.E.A., combined tensile, and combined tear failed to exhibit much improvement relative to combined T.E.A. alone. For these data, however, the combination of machine and cross-machine T.E.A. exhibits a modest improvement in correlation coefficient over combined T.E.A. alone.

Combined tensile and tear exhibit no significant relationship to the face drop performance of the 50-lb. extensible kraft sacks of the study. The same conclusion was reached when the M.D. and C.D. orientations were used.

Combined 50% R.H. Data for Flat and Extensible Kraft Papers

In the regressions involving combined T.E.A. and a second property, the multiple correlations exhibited little or no improvement over the simple correlation coefficient for combined T.E.A. alone (0.89). For example, in Fig. 3, combined T.E.A. and combined tear exhibit a multiple correlation coefficient of 0.89 which is equal to that exhibited by combined T.E.A. alone. Also combined tear was not a significant statistical factor in the relationship while combined T.E.A. was highly significant. It appears, therefore, that combined tear is not an important factor in the face drop performance at 50% R.H. of pasted sacks made from 50-lb. flat or extensible kraft.

As in the case of the flat or extensible kraft results the two-factor relationship involving combining tensile and tear was considerably inferior to the relationship obtained with combined T.E.A. alone.

While the multiple correlation coefficient for the combination of M.D. and C.D. T.E.A. is higher than the simple correlation coefficient for either direction separately, it is only equal to the correlation coefficient for combined T.E.A. alone. Thus, giving the directions equal weight in the combined value seems about as efficient as using the two directions in a two-factor relationship. It has been felt that this conclusion would not hold for all sack designs and shapes. For this reason the two-factor type of equation was favored in past work.

Combined 10, 25, and 50% R.H. Data for Flat and Extensible Kraft Papers

A limited number of relationships were investigated for the combined data - i.e., the 50% R.H. data from Studies I and II and the 10 and 25% R.H. data from Study II. A disadvantage of using the combined data for the three humidity levels is that the effect of R.H. on both commodities and paper are intertwined. Consequently, changes in paper properties with R.H. may be called upon to explain

changes in sack performance which are partly attributable to changes in the flow characteristics of the commodity. With this reservation, a number of the relationships studied are shown in Fig. 4.

Improvements in correlation coefficient and prediction ability were achieved using combined tear with combined T.E.A. The improvement in prediction accuracy relative to combined T.E.A. is especially noticeable for the 10 and 25% R.H. data.

For the regressions studied, the highest correlations were obtained using either C.D. T.E.A. or combined tear with the T.A. impact fatigue test.

Conclusions

Taking the 50% R.H. results as a whole, one general conclusion is that linear multiple property relationships offer no real advantage over linear single-factor relationships based on combined T.E.A. or some of the other paper properties.

For the composited data for flat and extensible papers, combined T.E.A. gave an average percentage prediction error of 18.4%. The average percentage prediction error for M.D. T.E.A. alone was 23.9% and for C.D. T.E.A. alone was 35.0%. Using combined T.E.A. about 65% of the predictions were within 15% of the observed value. Comparable figures for M.D. and C.D. T.E.A. were about 44 and 30%, respectively, within $\pm 15\%$ of the observed value. The poorer relative performance of C.D. T.E.A. in the above comparisons probably is a consequence of compositing the extensible papers with greater M.D. T.E.A. and sack performance with the flat kraft samples. The correlations within each type of sack paper indicated that C.D. T.E.A. gave better predictions of face drop sack performance than M.D. T.E.A. It seems reasonable, however, that C.D. T.E.A. alone would fail to predict the relatively great increases in sack performance obtained with extensible papers.

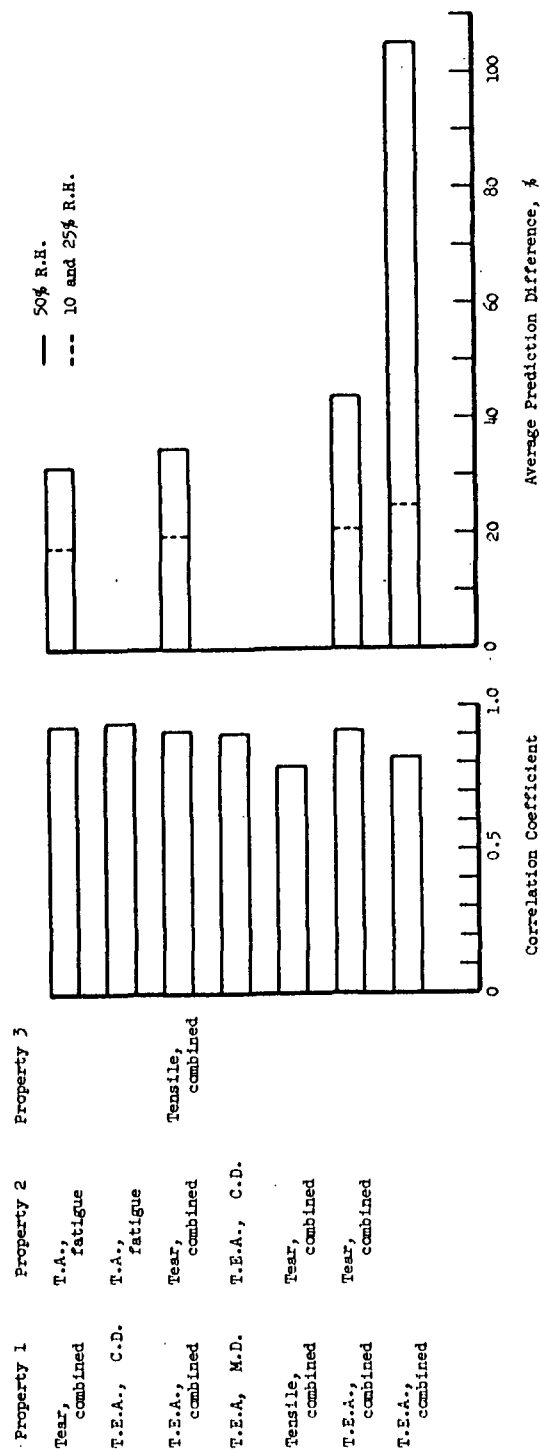


Figure 4. Comparison of Multiple Factor Relationships for Face Drop Performance at 10, 25 and 50% R.H.

It may be noted that all of the relationships fail to accurately predict the relative performance of certain sack papers. There are a number of possible reasons for the occasional larger discrepancies between predicted and observed face drop. These include the following:

1. Drop test variability. The variability of the sack drop test is relatively large. In general, the error of prediction cannot be better than the variability of the drop test itself. Because of the large variability, occasional large discrepancies between predicted and observed values may occur from this cause alone.
2. Fabrication quality. Creases, nesting, etc., may cause reductions in face drop performance which cannot be predicted by any of the tests used.
3. Sack paper properties. The properties evaluated herein may not accurately measure those characteristics of the sack paper which actually determine face drop performance. Also, certain properties may enter into face drop performance to a lesser degree and their influence may be overshadowed in the data of this study by the drop test variability, fabrication quality, etc.

BUTT DROP - SINGLE FACTOR RELATIONSHIPS

The properties giving the best and poorest predictions of butt drop performance are illustrated in Fig. 5 and 6, respectively.

Flat Kraft Sack Papers

Averaging the predictive ability for Studies I and II the five best sack paper tests for predicting butt drop were as follows:

- a. Frag, cross
- b. T.E.A., cross

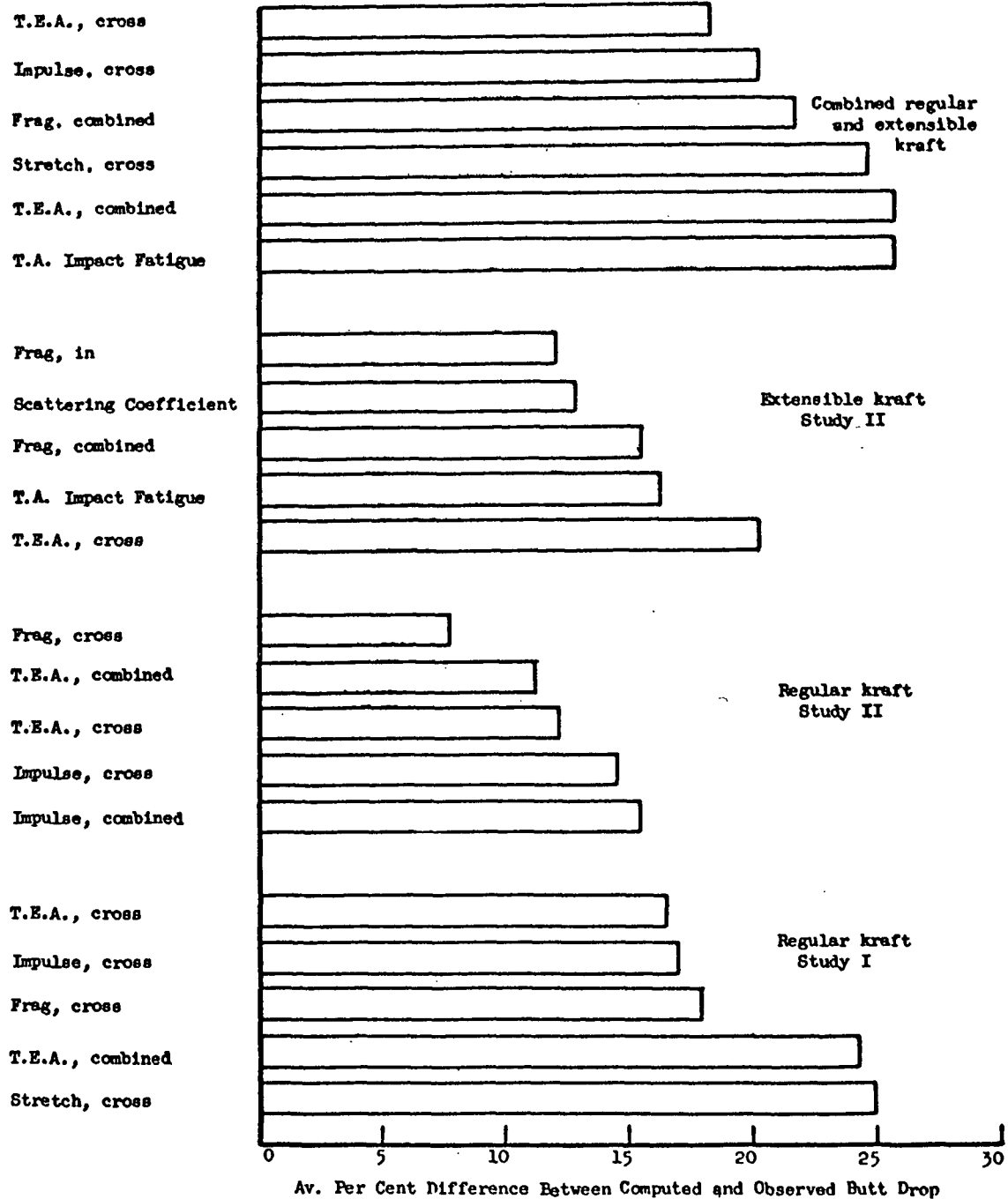


Figure 5. Comparison of Properties Giving the Best Predictions of Butt Drop Performance

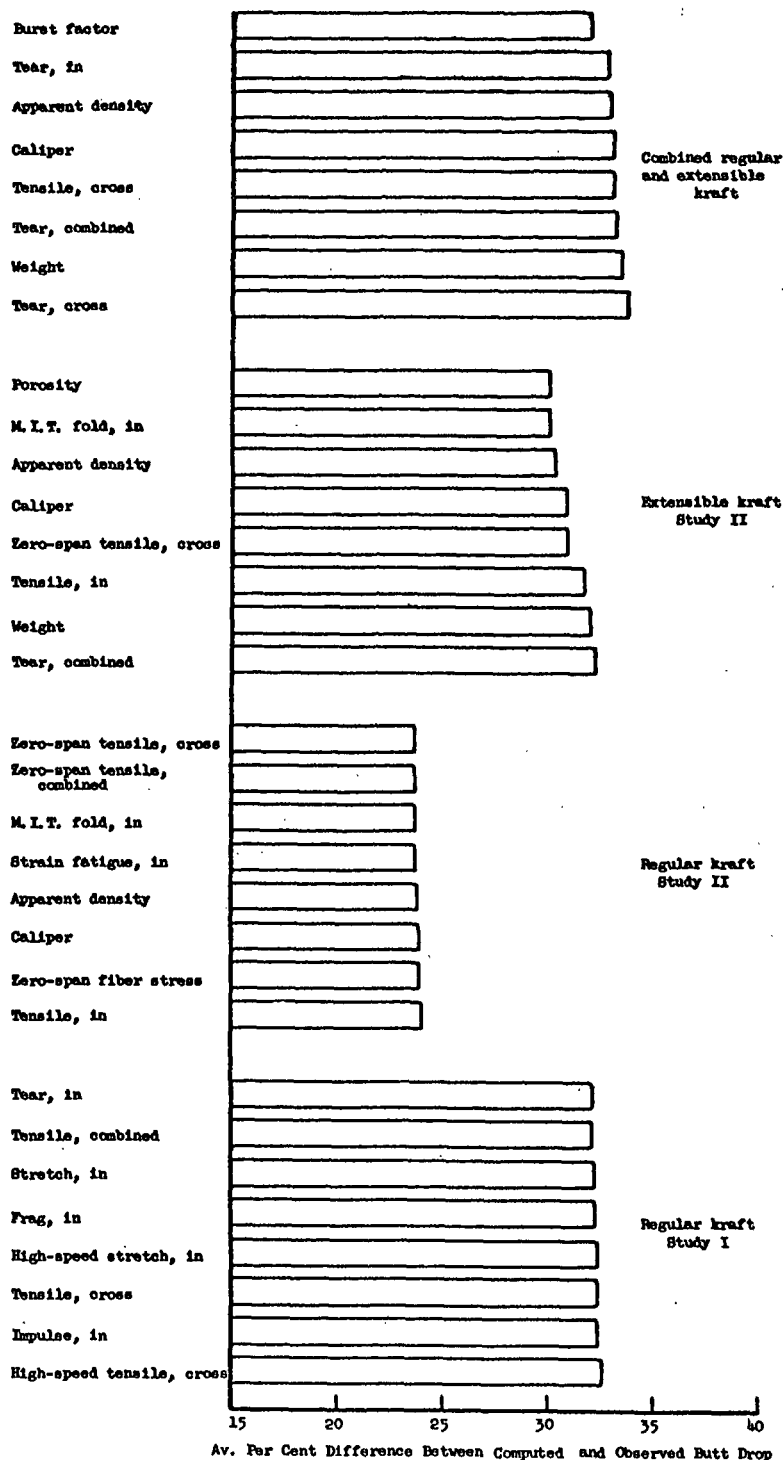


Figure 6. Comparison of Properties Giving the Poorest Predictions of Butt Drop Sack Performance

- c. Impulse, cross
- d. T.E.A., combined
- e. Frag, combined

Based on testing ease and calibration considerations, T.E.A. is preferred for specification or control of 50-lb. flat kraft sack paper. The cross-machine orientation is the dominant direction because the stresses in butt drop are believed to be predominantly in the cross-machine direction. It is believed, however, that the machine-direction characteristics have a minor influence in butt drop. Therefore, if a major change in the machine-direction T.E.A. is made, e.g., extensible kraft, an improvement in butt drop can be expected.

Extensible Kraft Sack Papers

The five best tests for predicting butt drop performance of extensible paper sacks (see Fig. 5) were as follows:

- a. Frag, in
- b. Scattering coefficient
- c. Frag, combined
- d. T.A. impact fatigue
- e. T.E.A., cross

Although scattering coefficient, Frag, and T.A. impact fatigue are better related to butt drop performance than cross-machine T.E.A., it is believed the latter is better adapted for use in control, etc.

Extensible and Flat Kraft Sack Papers

The six best tests arranged in order of decreasing efficiency were:

- a. T.E.A., cross
- b. Impulse, cross

- c. Frag, combined
- d. Stretch, cross
- e. T.E.A., combined
- f. T.A. impact fatigue

Disregarding the fatigue tests because of test time, calibration difficulties, etc., it appears that cross-machine T.E.A. is the best single property for the prediction of face drop performance of pasted sacks made from 50-lb. flat or extensible paper. Cross-machine T.E.A. is superior to combined T.E.A. for butt drop prediction because the importance of in-machine T.E.A. is overemphasized by the combined value.

For the combined data cross-machine T.E.A. gave predictions of butt drop performance within $\pm 15\%$ of the observed value in about 52% of the comparisons. About 70% of the predicted values were within $\pm 25\%$ of the observed butt drop values. The average difference in percent between observed and predicted values was near 18%. These predictions were obtained using the following equation:

$$B = -27.2 + 177.8 W_y \quad (2)$$

where B = butt drop at 50% R.H., safe inch

and W_y = cross-machine T.E.A., in lb./in.².

Equation (2) should not be used for general predictions of butt drop behavior since it strictly holds only for the particular constructions and evaluation conditions. The predictions are expected to hold under many conditions, however, on a relative basis when it is desired to compare the potential butt drop characteristics of various sack papers.

It is evident that predictions of butt drop based on cross-machine T.E.A. can be seriously in error at times. Butt drop tests can be affected quite seriously

by crease quality since failure frequently proceeds along the creases. In some instances poor predictions can be attributed to poor crease quality. This is examined in greater detail in the following section.

Butt drop appears to be relatively sensitive to changes in cross-machine T.E.A. Calculations based on Equation (2) show that changes of about 10% in C.D. stretch introduce changes in T.E.A. equivalent to about 20% change in butt drop.

BUTT DROP - MULTIPLE FACTOR RELATIONSHIPS

The preceding section was concerned with determining the degree of relationship between the various individual sack paper properties and butt drop. In addition, an extensive analysis was performed to determine if prediction accuracy could be materially improved using various combinations of conventional sack paper properties. The results obtained for a small number of the more promising relationships studied are shown in Fig. 7. For comparison, the results obtained with C.D. T.E.A. alone are also shown.

Flat Kraft Sack Papers

For these 50-lb. sack papers using C.D. T.E.A. in combination with C.D. tensile, C.D. or M.D. tear resulted in small or in some cases no improvement in correlation or prediction accuracy relative to C.D. T.E.A. alone. Relatively small improvements in correlation were obtained with M.D. and C.D. T.E.A.

As a result, C.D. T.E.A. seems to be the dominant property governing butt drop performance of flat kraft.

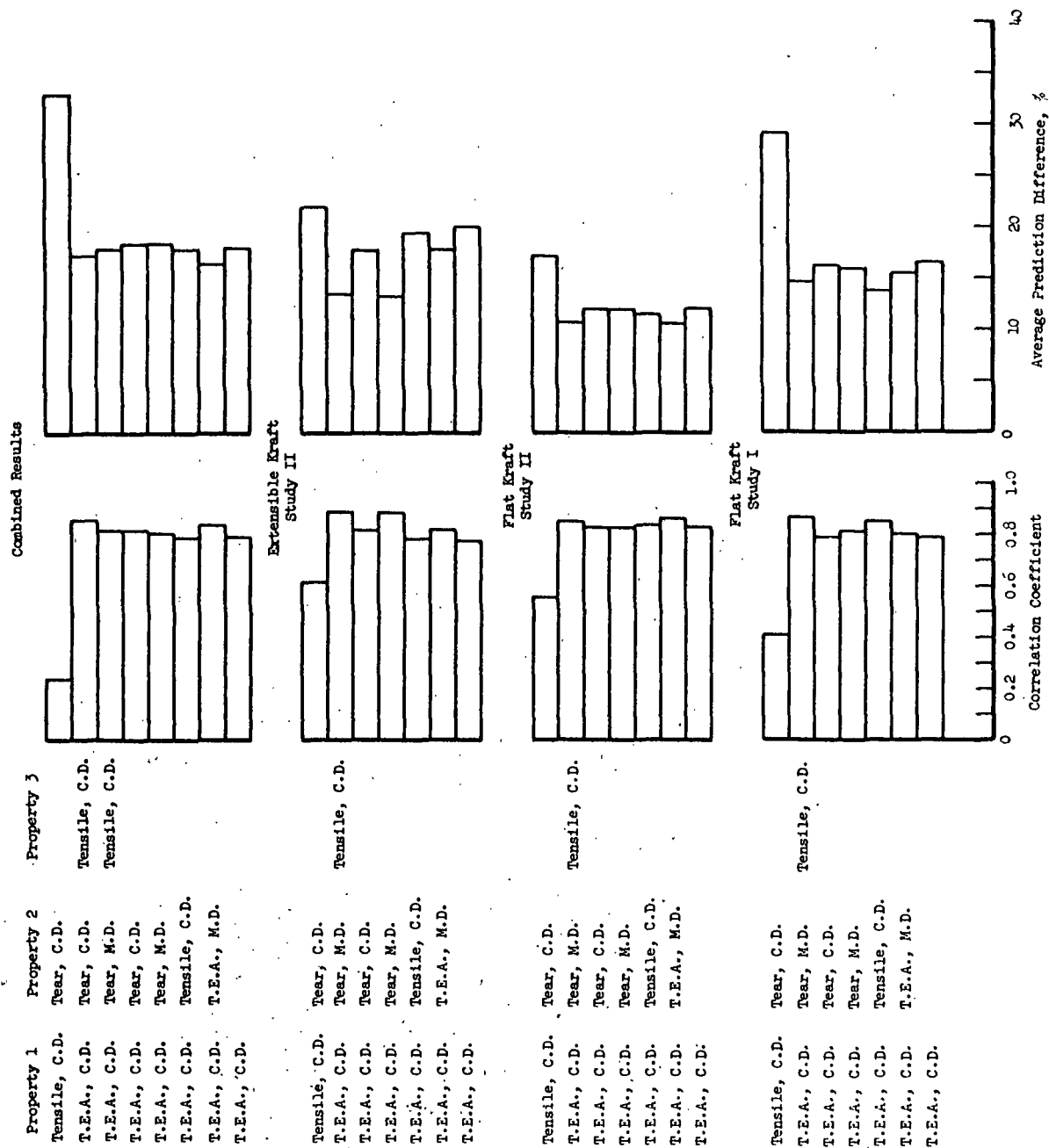


Figure 7. Comparison of Multiple Factor Relationships for Predicting Butt Drop.

Extensible Kraft Sack Papers

For the extensible kraft runs, the greatest improvements in correlation or prediction accuracy were obtained using C.D. T.E.A. in combination with M.D. T.E.A., or C.D. tear, or C.D. tensile. The three-factor relationship embracing C.D. T.E.A., M.D. tear, and C.D. tensile also gave improved correlations and predictions relative to C.D. T.E.A.

The improvements obtained with C.D. tear are surprising since the normal mode of failure in butt drop is a rupture in the lengthwise (M.D.) orientation of the sack - often along the crease. For this reason the relationship embracing C.D. T.E.A. and C.D. tear should be used with caution.

T.E.A. is a measure of the energy under the tensile load deformation curve. A given value of T.E.A. could, theoretically, be obtained in many different ways - e.g., high tensile and low stretch and vice versa. It can be speculated that butt drop performance will depend not only on C.D. T.E.A. but also, to some extent, on how the T.E.A. level is achieved - i.e., on the shape of the load deformation curve and on the ultimate tensile and stretch values. This may explain why the addition of C.D. tensile to the relationship tends to improve predictions. This matter could be investigated in terms of the fatigue theory advanced in Report Eighteen.

Combined Flat and Extensible Kraft Sack Papers

The greatest improvements in butt drop predictions relative to C.D. T.E.A. alone were obtained with the following equations for the combined data.

$$B = 16.9 W_x + 155.0 W_y - 25.6 \quad (3)$$

$$B = 187 W_y + 3.14 T_y - 0.74 E_y - 190.0 \quad (4)$$

where B = butt drop (50% R.H.), safe inch

$\frac{W}{-x}, \frac{W}{-y}$ = M.D. and C.D. T.E.A. in lb./in.²

$\frac{T}{-y}$ = C.D. tensile, lb./in.

$\frac{E}{-y}$ = C.D. tear, grams

Equation (4) gave the highest correlation (0.86) whereas Equation (3) gave the lowest average prediction difference (16.5%). As mentioned previously, the occurrence of C.D. tear in Equation (4) may be matter for concern because it does not seem entirely logical in view of the usual gross failure pattern for butt drop.

Equations (2) and (3) are illustrated in Fig. 8. The dashed lines are derived from Equation (3) and represent the relationship between $\frac{B}{-y}$ and $\frac{W}{-y}$ for three levels of M.D. T.E.A., namely 0.25, 1.0, and 1.5 in lb./in.².

The degree of predictive accuracy achieved with Equations (2), (3), and (4) is summarized below.

Prediction Range	Percent of Predictions Within Indicated Range		
	Based on C.D. T.E.A. [Eq. (2)]	Based on M.D. and C.D. T.E.A. [Eq. (3)]	Based on C.D. T.E.A., Tensile and Tear [Eq. (4)]
0-10	37.0	39.1	37.0
10.1-20	19.6	39.1	30.4
20.1-30	28.3	6.5	19.6
30.1-	15.2	15.2	13.0

On the encouraging side nearly 80% of the predictions based on Equation (3) were within 20% of the observed value. This was considerably better than was achieved using C.D. T.E.A. alone. On the other hand, about 13 to 15% of the predictions using any of the three equations were seriously in error - over 30%.

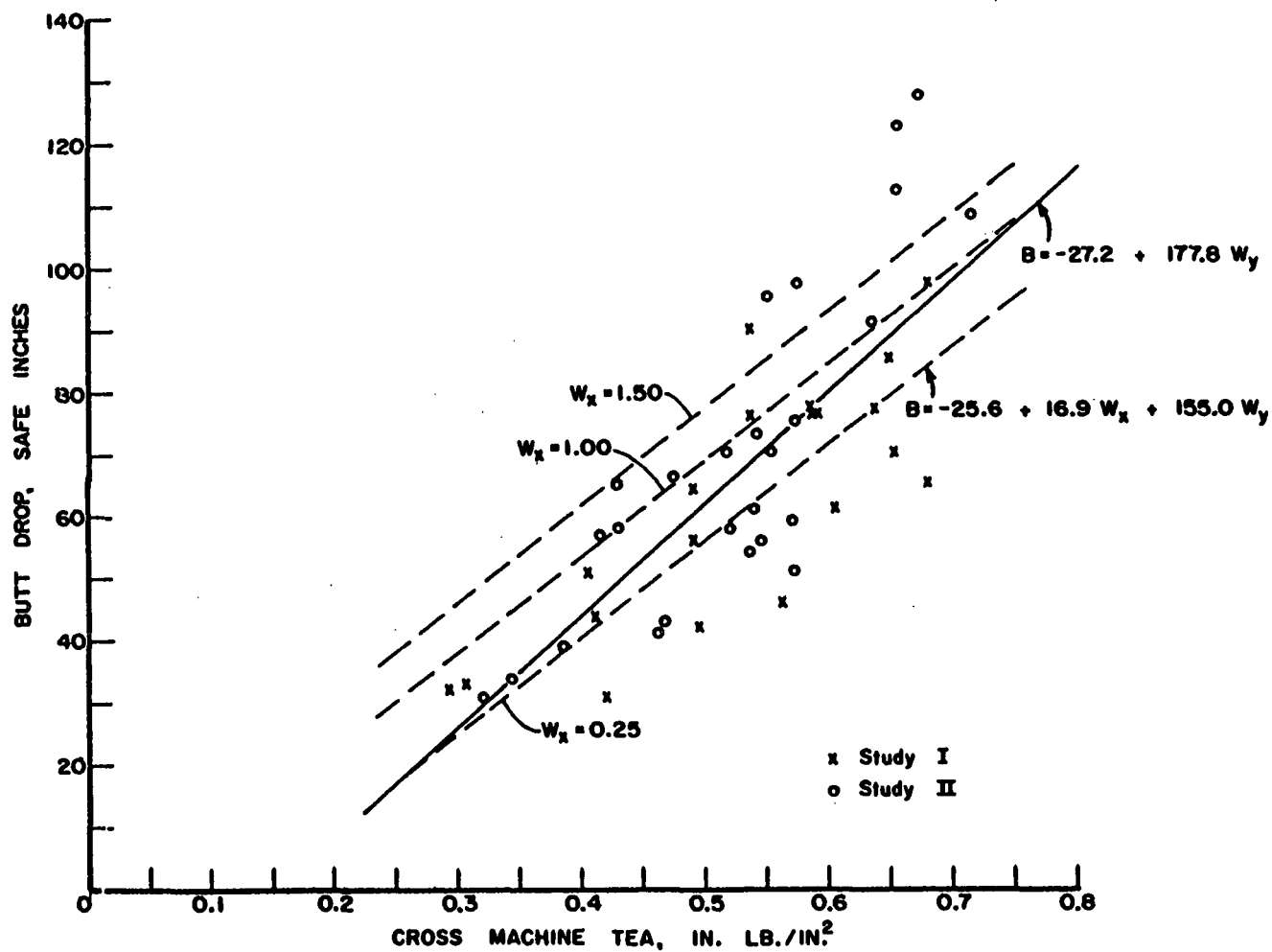


Figure 8. Relationship Between Butt Drop and Cross-Machine T.E.A.

For the flat kraft samples a number of the poor predictions could possibly be attributed to poor crease quality. This did not seem to be true for the extensible kraft samples. Butt drop must be influenced by crease quality to a considerable extent since failures frequently progress along the side crease. Better methods of evaluating crease quality would probably improve predictions - particularly of flat kraft papers.

MECHANICS OF SACK IMPACT

Efforts have been directed to developing and utilizing an electrical resistance strain gage for the measurement of strains induced in a multiwall sack during impact. Conventional wire strain gages are undesirable because they reinforce the sack paper and thereby decrease the strain and disturb the natural strain patterns in the sack. The gages under development are constructed by spraying a graphite solution onto the outer ply of a sack over a limited rectangular area defined by a template. Measurement of the change in electrical resistance of the graphite during sack impact can be related to strain, and hence indirectly to stress or energy absorption.

Measurements of this type should be invaluable for determining the nature, magnitude, and distribution of stress and strain in a sack during impact. This information can be expected to lead to a better understanding of the required strength of sack paper, the balance of properties in the two principal directions of the sheet, and the effect of other variables on sack performance (such as sack dimensions, commodity, impact conditions, and environmental variables).

The results of this investigation may be grouped in the following three categories: (a) development of a graphite strain gage, (b) measurement of impact strain in multiwall sacks, and (c) interpretation of the impact data in terms of

a mathematical model of the impact of a paper strip by a mass such as the commodity in a multiwall sack. The major conclusions in each category are as follows.

DEVELOPMENT OF A GRAPHITE STRAIN GAGE

Graphite strain gages constructed with a commercially-available graphite solution (Spray-Graph) have the following desirable characteristics:

1. The gages are very sensitive to strain -- on the order of twenty-five times more sensitive than commercial wire-grid or foil gages.
2. The reproducibility between gages with respect to calibration is about 4% (coefficient of variation). This is substantially better reproducibility than was achieved in earlier trials with brushed-on graphite gages or conductive films.
3. The gage is relatively easy to construct by spraying.
4. Based on earlier studies, the graphite gage provides negligible reinforcement to the sack paper.

The following characteristics are less than desirable in a strain gage, but can be accommodated:

5. When used in repeated tension, as occurs in repeated sack impact, the gage provides an accurate determination of strain only if the maximum strain attained in a given cycle is greater than the maximum strain of the preceding cycle. This condition appears to be satisfied in the progressive height face drop test of multiwall sacks. The restriction arises because the graphite gage has incomplete electrical recovery at the end of a cycle in repeated tension (incomplete beyond that attributable to nonrecoverable stretch in the sack paper).

6. Allied to item 5 above, the applied strain in a cycle of repeated tension (i.e., total strain minus nonrecoverable strain at the end of the preceding cycle) cannot be estimated easily or with as high an accuracy as total strain.

7. Taken together, Items 5 and 6 reveal that this graphite gage is primarily useful for indicating the total strain in the paper during impact, relative to the virgin unstrained state of the material. This is useful and meaningful information inasmuch as paper fails in repeated tension when the total strain exceeds the virgin stretch.

8. Unlike commercial strain gages, a rectangular graphite gage has high sensitivity to strain applied transverse to the direction for which strain is intended to be measured. Transverse strains exist in a multiwall sack because the strains during impact are biaxial. Hence, the response of a single gage reflects both machine- and cross-machine strains and a gage by itself cannot separate the two effects. The transverse sensitivity is high because the gage is essentially an area deposit rather than a filament as in commercial gages. Limited experiments indicate that the transverse sensitivity does not depend upon the length-to-width ratio of the gage (a rectangular deposit has the same sensitivity as a square deposit), but rather depends upon the degree of reinforcement provided by connection of electrical lead wires at the ends of the gage. Large errors can be incurred in estimates of longitudinal strain if the transverse sensitivity is ignored - errors demonstrably as high as 100%, depending on the ratio of machine-to-cross-direction strain. Corrections can be made to remove the effect of transverse sensitivity; this involves (a) calibrating the transverse as well as longitudinal sensitivity of the gage, (b) mounting two gages perpendicular and in close proximity to each other on the sack, and (c) applying a correction calculation developed in this report.

9. Although only one sample of sack paper was used in this study, it may be anticipated that the calibration of a graphite gage (both longitudinal and transverse) is specific to a given sample of sack paper. This supposition is based on the concept that the electrical conductivity of the graphite deposit depends on the mechanical contact of the graphite particles, which in turn should depend upon the internal geometry of the paper sheet on which the graphite is deposited. Earlier work with a similar graphite material revealed that longitudinal sensitivity of the gage differed between flat kraft and extensible kraft.

In view of the nine results discussed above, it is concluded that graphite gages of the type studied here provide a means of measuring strain in sack paper, although the gages have several troublesome points requiring special considerations not normally of concern in conventional strain gage technology.

MEASUREMENT OF IMPACT STRAINS IN MULTIWALL SACKS

Graphite gages were constructed on the outer ply at the center and edges of the face of two multiwall sacks (12% extensible sack paper) so as to measure the cross-direction strain across the face at midlength. A fourth gage was oriented in the machine-direction at midlength to permit correcting for transverse sensitivity of the gages. The sacks were filled with 94 lb. of cement and subjected to a progressive height face drop test starting at two feet. Analysis of the impact strain data revealed the following:

10. In general, the nonrecoverable strain in the sack paper increased with each succeeding drop.

11. In general, the maximum total strain during impact increased with each succeeding drop.

12. Items 10 and 11 confirm that in a progressive height face drop the sack paper exhibits the expected behavior corresponding to repeated tension, namely, progressively increasing total strain and progressively increasing nonrecoverable stretch. This observation verifies that at least in principle sack impact involves fatigue performance of sack paper in repeated tension, as has been studied extensively in previous investigations of Project 2033.

13. The maximum cross-direction strain just prior to sack failure was approximately 5% and occurred at the center of the sack. In view of the fact that these sacks failed in cross-direction tension (machine-direction rupture line) this maximum strain compares favorably with the Instron virgin stretch (5.5%) for this sample of paper, but unfavorably with Plastechon high-speed virgin stretch (<2.8%). The discrepancy with high-speed stretch possibly may be attributable to calibrating the graphite strain gages statically.

14. The machine-direction strain near the center of the face just prior to sack failure was about 6%. This is less than Instron virgin stretch (12%) and Plastechon high-speed virgin stretch (between 6.3 and 9.5%), as would be anticipated since the sacks did not fail in machine-direction tension.

15. It is seen that the machine- and cross-direction total strains are in the ratio of about 1.2 at the time of sack failure.

Impact strain measurements of cross-direction strain in a constant height drop test were also made with seven conventional SR-4 wire-grid strain gages which spanned the width of the sack face at midlength. The results of these measurements are discussed in connection with the following third category of this study.

INTERPRETATION OF DATA IN TERMS OF A MATHEMATICAL MODEL OF IMPACT

The behavior of a strip of sack paper across the face of an impacted sack may be likened to that of a rod impacted at each end by a finite mass, for which a classical theoretical analysis exists. Although the theoretical model is a gross simplification of the corresponding strip in the sack, the model has enough similarities to provide an effective focal point for examination of the sack impact data. For example, the model provides formulas for the intensity and distribution of stress (or strain) as a function of time in terms of sack paper properties (modulus of elasticity and sonic velocity), dimensions, commodity density, and impact velocity. An attractive aspect of the theoretical model is that it takes account of the deceleration of the commodity as it "explodes" outward against the sidewalls of the sack, which is certainly an essential aspect of sack impact. On the other hand, the model does not consider the effects of biaxial and/or inelastic stresses or the compressibility of the commodity. Nevertheless, the simplified model is believed to offer a worthwhile starting point for interpretation of experimental data from sack impact.

Four theoretical results of the mathematical model may be tested against the experimental strain data obtained with graphite or SR-4 strain gages. They are:

16. Strain vs. time at a given location on the sack. Theoretically the strain at a given location should increase in a series of abrupt jumps as time progresses, with a decay in strain between jumps. About 50% of the experimental strain records exhibited one jump. Neither the abruptness of jump nor the number of jumps was as great as anticipated by theory; the disparities may be attributable to compressibility of the commodity and inelastic effects. The jumps are of some interest because the model offers an alternative to an earlier belief that the

jump is the result of a pseudo-impact caused by compression of air between sack and drop tester base followed by the major impact.

17. Distribution of strain. According to theory, the maximum strain experienced at the center of the sack in any given drop should exceed the strain at the edge of the sack. The observed ratio for the sacks of this study was 1.7, on the average, indicating compatibility with theory. Herein may lie an explanation for the high frequency of failures near the center of the sack face (cross-direction tension failure, machine-direction rupture line) since the center region of the sack should experience the highest strains.

18. Duration of strain. On the reasonable assumption that the impact velocity is related to the drop height, the model predicts that the duration of strain build-up (time interval from zero to maximum strain) should be independent of drop height. The graphite-gaged sacks were tested in progressive height face impact ranging from 2 feet to 9-1/2 feet. The duration of strain was independent of drop height, thereby showing agreement with the theoretical model.

Duration of impact is defined as the time interval during which strain exists at a given location (zero to maximum to zero strain). An estimate of duration for sack impact, based on the theory, is six milliseconds. The actual duration (which could not be determined exactly) appears to be about an order of magnitude greater than theory. This extent of discrepancy is not considered to be excessive in view of the likely effects of nonflat drops, compressibility of commodity, biaxial stresses and inelastic effects, of which the model takes no account.

19. Propagation of strain. The propagation (i.e., travel) of stress or strain from edge to center of the sack is an essential part of the theory. Although not measured very precisely and confused by occurrence of nonflat drops, the

experimental data show a definite trend of strain propagation from edge to center of the sack. The observed transit times were about 0.3 millisecond, on the average, as compared with 0.1 millisecond according to theory. The disparity is not excessive. The results indicate that wave propagation is an inherent consideration in sack impact.

In summary, there is reasonably good qualitative agreement between the simplified impact model and the experimental strain measurements. This is encouraging and indicates that there is much of value to be learned by experimental strain analysis coupled with a theoretical understanding of sack impact. When sack impact behavior has been more fully explored in these fundamental terms it should be possible to extract a wealth of useful information for the papermaker, the sack designer, and the user. The mechanical analysis of impact, along with improved methods of paper evaluation, should tell the papermaker those properties of his paper that are important to sack performance. These are the properties that should be controlled at the end of the paper machine and at earlier stages of machine operation, refining, pulping, and possibly in selection of fiber.

Although sack dimensions may seem to be the province of the sack designer, it is evident that there is an interplay between paper properties and sack dimensions which has implications for the papermaker in the strength levels required and in the balance of properties in the two principal directions of the sheet. Work in Project 2033 has shown that the performance of given sack paper can be enhanced by an appropriate ratio of length-to-width dimensions of the sack. This is a "two-way street" and as more understanding develops regarding the fundamental properties involved it may be possible to produce paper which best accommodates sack dimensions fixed by user specifications or trade practices.

There seems little doubt that sack fabrication factors (creases, folds, adhesive patterns, etc.) influence sack behavior -- both in altering the properties

of the parent paper and in setting up stress concentrations where there are abrupt changes in plies of paper or in sack geometry. A thorough understanding of stress distributions in the sack during impact is indispensable for isolating undesirable fabrication effects and to point the way to rectifying them.

Lastly, it is far from trite to recognize that the stresses of sack impact are generated by a commodity. It seems evident that production or selection of sack paper to do a specified job should be as intimately concerned with the commodity as with dimensions, sack design, and environment. In this view, the role of the commodity in sack impact is an integral part of the larger problem.

These are some of the prospects for sack technology which can be expected to be realized once the mechanics of sack impact is understood. The task is not an easy one; it demands depth in concept, theory, experiment, instrumentation, and support. It is firmly believed that only through fundamental studies of this type can the long-term interests of the sack paper industry best be served.

LOCAL STRAIN IN PAPER UNDER TENSILE STRESS

Based on numerous studies which have been carried out, it may be deduced that the failure of a multiwall paper sack from internally generated impact may take place primarily as a two-step process. First failure occurs in a local area due to the rupture of bonds and/or fibers due to tensile stress. The initiation of failure causes a concentration of stress at the boundaries of the local area, or areas as the case may be, which coupled with the elastic energy in the paper and/or commodity, causes the initial failure to propagate in the sack paper. The failure pattern observed in a sack, resembling a continued tear, is believed to

represent primarily post failure phenomenon as the area of initial failure is probably very small compared to the final area of failure.

It is readily apparent that paper is not a uniform, homogeneous material. This lack of uniformity may be expected to lead to marked irregularity in the distribution of strain in a sheet. Any irregularity in the distribution of strain could lead to a distinctly lower sheet strength than would otherwise be the case.

The irregularity in strain raises a number of interesting questions. Among these are:

1. Does failure occur in the zone of highest local strain?
2. Do the local areas of greatest strain at low levels of stress also exhibit the greatest strain at or near rupture?
3. At a given level of stress the areas of greatest strain could be beyond the proportional limit and the areas of least strain within the proportional limit. If such a situation occurs the modulus of elasticity will be different for these areas and raises the question as to whether the sonic velocity varies from area to area.

Although a great deal of information is available on the average mechanical properties of paper little data have been published on the local values of the properties. A study was undertaken, therefore, to determine the variation that occurs in magnitude of local strain in kraft sack papers under tensile load.

For this purpose tiny glass beads were attached at 2-mm. intervals to tensile specimens and the changes in length of the segments were measured photographically during the tensile testing of 50-lb. regular and extensible kraft sack paper. The results indicated the following:

1. Regions of high and low strain were usually found to continue through several of the two-millimeter intervals. Initial and secondary rupture, the latter occurring on restraining the longer remnant remaining after the initial rupture of the virgin specimen, usually occurred in or near regions of greatest strain.

2. Measurements of strain made on the right-hand, left-hand, and center sections of the same tensile specimen exhibited marked variations in their magnitude within each section and also between sections.

3. Normally the regions of greatest strain at low levels of stress also show the greatest strain at high levels of stress.

4. For regular kraft sack paper Poisson's ratio was approximately 0.2.

5. The lateral contraction of extensible paper was very small at relatively low levels of strain; however, above 4% longitudinal strain, Poisson's ratio was approximately 0.2.

TENSION PROPERTIES OF SACK PAPER AT HIGH RATES OF STRAIN

High-speed uniaxial tensile tests were performed on six samples of multi-wall sack paper as part of a continuing attempt to better simulate the behavior of sack paper as it performs in a sack. One objective was to explore the possibility of obtaining improved correlations between sack performance and paper quality evaluated by means of a modern, high-speed tension testing machine. A second objective was to determine whether high-speed tension properties may help explain the relatively poor sack performance of three of the samples of paper; conventional and other special test properties of these samples had not been adequately reflected in sack performance.

The high-speed tests were performed on a Plastechon Model 581 Universal testing machine at test rates of 1000, 10,000, and 15,000 in./min. (six-inch span).

Slow-speed tests of these samples had been performed previously with an Instron testing machine at 0.5 in./min.

Among the conclusions which may be drawn from this study are the following:

1. In general, increasing test rate caused (a) an increase in tensile strength, (b) a decrease in stretch, and (c) a decrease in tensile energy absorption (T.E.A.) for both principal directions of the paper.
2. High-speed and low-speed (Instron) tension properties appeared to be quite well correlated in the machine direction of the papers. High test rates decreased the differences between papers with respect to cross-direction stretch and tensile energy absorption, but increased the differences in tensile strength.
3. There was no indication that high-speed tensile energy absorption correlates better with sack performance than Instron energy absorption.
4. High-speed tension properties failed to explain the relatively low sack performance of three of the samples of sack paper.
5. This study provides valuable data on the magnitudes of load, stretch, and energy absorption at high rates of strain which should be useful in the study of the mechanics of sack impact.

Many of the high-speed load-elongation curves exhibited an oscillatory shape prior to rupture. Specimens having high stretch (machine direction of the extensible papers) exhibited multiple peaks in the load-elongation curve which could not be attributed to any of several well-recognized "side effects" in high-speed testing ((resonance or "ringing" of the load transducer, stress wave reflections, and bounce in the slack adapter at the lower clamp). However, the shape of the curves with multiple peaks strongly suggests the presence of an instrument vibration of undetermined origin. The tension data at 1000 in./min. are more reliable than at 10,000 and 15,000 in./min. because of the possibly extraneous

nature of the multiple peaks in the load-elongation curves at the latter rates. On the other hand, the multiple peaks possibly may be a unique characteristic of the behavior of fibrous structures at high rates of strain. An understanding of the mechanism causing multiple peaks may be important to the use of paper in service applications involving high rates of stress and strain.

SONIC MEASUREMENTS ON SACK PAPER

This study falls in the area of materials science and is part of a continuing attempt to better simulate in paper evaluation the behavior of sack paper during sack impact.

When a force or displacement is applied at one point of a body, a finite, though usually small, interval of time is required for the effect to be felt at a remote point in the body. The disturbance propagates as a wave at the speed of sound in the body. The rate at which the disturbance propagates is termed the sonic velocity, c , and is related to modulus of elasticity, E , and density, ρ , approximately as follows:

$$c = \sqrt{E/\rho} \quad (5)$$

Sonic velocity appears to enter into the impact behavior of a sack because it is a property of the sack paper governing (along with other factors) the magnitude and distribution of strain and the duration of the impact. Sonic velocity is attractive from the standpoint of materials testing because with present-day instruments it provides a rapid, nondestructive measurement of modulus of elasticity, E , (and hence stiffness of the paper) at dynamic rates.

The sonic velocities (and hence the "sonic moduli of elasticity") have been evaluated for the samples of sack paper from the second fabrication program. The measurements were made by means of a Morgan Dynamic Modulus Tester Model PPM-5.

The sonic moduli were compared with the Instron moduli obtained at conventional test rates. Theoretically, the sonic modulus should be greater than the Instron modulus because: (a) Equation (5) neglects an effect due to Poisson's ratio in sheet materials such as paper, and (b) the effect of increased test rate is probably to increase modulus. While this relationship held for extensible kraft papers, it was reversed for regular kraft papers (by a few percent, on the average). Further study of this effect is desirable in order to reconcile theory and the experimental method and/or test instrument.

An implication of the data is that extensible kraft sack papers are considerably more rate sensitive than are regular kraft sack papers. A point of possible interest is that three samples of sack paper having unexplainably low sack performance in terms of conventional properties, exhibited large increases (as high as 32%) in sonic modulus relative to Instron modulus. This implies that these samples are more "brittle" at dynamic rates and may be a possible reason for their low performance in sack impact.

Further analysis of the data is in progress, in regard to gaining a better understanding of the test and the relationship of sonic velocity or modulus to sack impact performance.

PRESSURE-TYPE BIAXIAL TESTER FOR SACK PAPER

During impact the paper in a multiwall shipping sack is stressed in tension in both principal directions, that is, biaxial tension. It is desirable, therefore, to have a method of evaluating sack paper in biaxial tension which will be meaningful to its performance in a sack. While there are several commercial sack paper testers which induce biaxial stresses (e.g., Couch-Muldoon and Frag impact testers), none of them can be considered as providing a fundamental

measurement of stress, strain, or energy absorption. An earlier attempt at constructing a biaxial tester in Project 2033 was less than satisfactory because it was evidently incapable of reaching the ultimate strength of sack paper for reasons of stress concentrations in the specimen.

A different type of biaxial tester has been constructed as one phase of research in Project 2033 and is currently being used to evaluate samples of sack paper from the second fabrication program. The tester induces biaxial tension in a circular specimen by means of pressure applied through a rubber membrane against one surface of the specimen. The tester is constructed along the lines of a bursting strength tester. Major differences, however, are that (a) the specimen is of 8-inch diameter and thus has available space for instrumentation to measure strain, distention, and energy absorption as well as pressure, and (b) the design will permit later modification into a fatigue tester or a high-speed biaxial tester.

The test apparatus may be viewed in either of two lights. On the one hand, it may be used simply as a testing machine for evaluation of biaxial energy absorption for purposes of correlation with sack performance. Energy absorption is estimated from continuous measurement of pressure and distention at the center of the specimen.

Viewed in another light, the sack paper specimen is a test structure, simpler than a multiwall sack, which may be used for studying fundamentally the relationship between biaxial tension and uniaxial tension. For example, a worthwhile objective is to find the relationship between biaxial and uniaxial tensile energy absorption and/or stretch. This information would permit evaluating paper samples by means of conventional uniaxial tensile tests and interpreting the results in terms of potential biaxial performance in sacks. Work directed to this goal is

underway with respect to energy absorption. It is planned to extend this work to include stretch.

Studies in this area of materials science, in conjunction with structural analysis of the finished sack, is a necessary and desirable phase of a balanced research program for sack paper. It is through a more fundamental understanding of the mechanical behavior of sack paper that we can expect to learn the means of improving its performance in the finished sack.

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